THE EFFECT OF STACKING SEQUENCE ON MECHANICAL PROPERTIES OF ALUMINIUM MESH REINFORCED WITH HYBRID COMPOSITE LAMINATES

A SYNOPSIS

Submitted by

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(Reg. No. 920210003)

in partial fulfillment for the award of the degree of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL, AERO, AUTO AND CIVIL ENGINEERING

KALASALINGAM ACADEMY OF RESEARCH AND EDUCATION

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TAMIL NADU, INDIA

SEPTEMBER 2024

1. INTRODUCTION

The integration of natural fibers into composite materials has gained significant attention in recent years due to their environmental benefits and mechanical properties. This introduction provides an overview of natural fibers such as jute, hemp, banana, and bamboo, as well as their combination with basalt woven fiber metal laminates (WFMLs) and aluminum diamond micro-expandable mesh (Al-DMEM). It also covers stacking sequences, Fick's distribution, mechanical properties, Hollow Hybrid Structural (HHS) tubes, and roll-wrapping techniques used in crashworthiness tests.

Jute fibers are widely recognized for their high tensile strength, low cost, and biodegradability, making them an attractive choice for composite materials. Jute composites have been extensively studied for their mechanical properties, including tensile, flexural, and impact strength. Recent studies have focused on improving the adhesion between jute fibers and polymer matrices to enhance the overall performance of jute-based composites [1]. Hemp fibers, known for their strength and durability, are another popular natural fiber used in composite materials. Researchers have explored the potential of hemp fibers in various applications, from automotive to construction, due to their sustainable nature and mechanical performance [2]. Banana fibers, derived from the pseudo-stem of banana plants, are lightweight and possess good mechanical properties. Banana fiber composites have been found to have high tensile and flexural strength, making them suitable for various structural applications. Studies have shown that treating banana fibers with alkali improves their interfacial bonding with polymer matrices, enhancing the mechanical properties of the composites [3]. Bamboo fibers are renowned for their high tensile strength and rapid growth, making them a sustainable resource for composite materials. Bamboo fiber composites exhibit excellent mechanical properties and have been used in various applications, including automotive and construction industries. Incorporating bamboo fibers into polymer matrices has been shown to improve composites' tensile and flexural strength [4]. Basalt fibers, derived from volcanic rocks, are known for their excellent mechanical properties, including high tensile strength and thermal stability. Basalt Woven Fiber Metal Laminates (WFMLs) combines basalt fibers with metal sheets, resulting in composites with superior mechanical properties. These laminates are suitable for high-strength and durability applications, such as automotive and aerospace industries [5].

Aluminum Diamond Micro Expendable Mesh (Al-DMEM) is a reinforcing mesh used to enhance the mechanical properties of composite materials. The diamond-shaped micro-expandable mesh balances strength and flexibility, making it suitable for various industrial applications. The use of Al-DMEM in hybrid laminates improves their tensile strength, flexural strength, and impact resistance [6]. The mechanical properties of Hybrid Woven Fiber Metal Laminates (HWFMLs) are critically dependent on the stacking sequence of the fibers and metal layers. Different stacking sequences result in varying mechanical properties, such as tensile strength, flexural strength, and impact resistance. Researchers have studied the effects of varying stacking sequences on the mechanical performance of HWFMLs to optimize their properties for specific applications [7].

Compression molding is widely used for fabricating plates, providing excellent control over fiber alignment and density, leading to improved mechanical properties. This method allows us to produce high-quality composite plates with consistent performance characteristics [11]. Roll-wrapping techniques are used to fabricate composite materials to ensure uniform layering and alignment of fibers and metals. This technique is beneficial in producing HWFMLs, where precise control over the layering process is essential for optimizing their mechanical properties. Studies have shown that roll-wrapping techniques significantly improve hybrid laminates' tensile strength, flexural strength, and impact resistance [10]. Fick's law of diffusion describes the diffusion process in materials, which is critical in understanding the moisture absorption behavior of natural fiber composites. Incorporating natural fibers into composites can influence their moisture resistance, making Fick's distribution an essential aspect of their study. Researchers have used Fick's law to model the moisture absorption behavior of natural fiber composites and optimize their performance in varying environmental conditions [8]. The mechanical properties of HWFMLs, such as tensile strength, flexural strength, and impact resistance, are essential for their application in various industries. Hollow Hybrid Structural (HHS) tubes are one application where these properties are critical. HHS tubes reinforced with natural fibers and Al-DMEM exhibit superior mechanical properties, making them suitable for applications requiring high strength and durability [9].

Crashworthiness tests are conducted to evaluate composite materials' impact resistance and energy absorption capacity. HWFMLs reinforced with natural fibers and Al-DMEM have been subjected to crashworthiness tests to determine their suitability for

automotive and aerospace applications. These tests have shown that hybrid laminates exhibit excellent energy absorption and impact resistance, making them ideal for high crashworthiness applications [11].

2. LITERATURE REVIEW

Hybrid Fiber Reinforced Polymer (FRP) composites have emerged as promising materials due to their enhanced mechanical properties and environmental benefits. These composites combine different types of fibers to optimize properties like strength, stiffness, and impact resistance while potentially reducing costs and environmental impact. This review covers various studies on hybrid FRP composites, focusing on the types of fibers used, their mechanical properties, and their applications. Natural fibers such as jute, flax, hemp, and Basalt have been extensively studied for their potential to replace synthetic fibers like glass and carbon in hybrid composites. Amruth et al. [12] have investigated the mechanical characteristics of basalt/epoxy laminates, demonstrating their high strength and durability. Similarly, Bakhori et al. [13] have examined the physical, mechanical, and perforation resistance properties of natural-synthetic fiber interply laminate hybrid composites, highlighting the significant performance improvements when combining natural and synthetic fibers. Another study by Neto et al. [14] reviewed recent advances in hybrid natural fiber-reinforced polymer composites, emphasizing the potential of natural fibers to enhance the mechanical properties of composites while being environmentally friendly. Jamshaid and Mishra [15] reviewed basalt fibers, discussing their mechanical and thermal properties and their potential as a sustainable alternative to synthetic fibers. The type and arrangement of fibers influences the mechanical properties of hybrid FRP composites. Mirzamohammadi et al. [16] explored the impact of carbon nanotubes on the tensile and impact properties of fiber metal laminates fabricated with jute/basalt fabrics and aluminum layers, demonstrating significant improvements in strength and impact resistance. Mirzamohammadi et al. [17],[18] the same group, also studied the flexural and shear performances of laminated aluminum/jute–basalt fibers epoxy composites, highlighting the benefits of hybridizing natural fibers with advanced materials like carbon nanotubes. Boopalan et al. [19] investigated the mechanical and thermal properties of jute and banana fiber-reinforced epoxy hybrid composites, finding that combining these fibers enhanced mechanical performance and thermal stability. Prasad et al. [20] examined the

mechanical performance of jute and basalt fiber geo-grid-reinforced epoxy hybrid composite materials, showing significant improvements in tensile and flexural strength. Hybrid FRP composites are used in various applications due to their superior mechanical properties and environmental benefits. Alshahrani et al. [21] highlighted the potential of jute-basalt reinforced epoxy hybrid composites for lightweight structural automotive applications, demonstrating their suitability for reducing vehicle weight while maintaining structural integrity. Zareei et al. [22] explored the bending and impact properties of laminated aluminum-hybrid basalt and jute fibers-epoxy composites, showing their potential for structural applications in the construction and automotive industries. Similarly, Bakhori et al. [13] examined the crashworthiness performance of hybrid kenaf/glass fiber reinforced epoxy tubes, emphasizing their potential for energy absorption applications in the automotive and aerospace sectors. Using natural fibers in hybrid FRP composites offers significant environmental and economic benefits. Natural fibers are renewable, biodegradable, and have less environmental impact than synthetic fibers. Moreover, they are often cheaper and lighter, contributing to the overall sustainability of composite materials. Neto et al. [14] emphasized the environmental benefits of using natural fibers in hybrid composites, highlighting their potential to reduce the carbon footprint of composite materials. Additionally, combining natural and synthetic fibers can save costs by reducing the amount of expensive synthetic fibers needed. This is particularly relevant in industries where cost and environmental considerations are critical. Jamshaid and Mishra [15] discussed the economic benefits of basalt fibers, highlighting their potential to replace more expensive synthetic fibers in various applications. Despite the advantages of hybrid FRP composites, several challenges must be addressed to realize their full potential. One of the main challenges is ensuring the compatibility and adhesion between different types of fibers and the matrix material. Mirzamohammadi et al. [18] investigated the effect of hybridizing natural fibers and adding montmorillonite nanoparticles on the impact and bending properties of eco-friendly metal/composite laminates, highlighting the need for improved interfacial bonding. Another challenge is the variability in the properties of natural fibers, which can affect the consistency and predictability of composite materials. This variability can be addressed through proper selection, treatment, and processing of natural fibers. Zareei et al. [23] studied the interlaminar shear strength and tensile properties of environmentally friendly fiber metal

laminates reinforced by hybrid basalt and jute fibers, emphasizing the importance of optimizing fiber treatment and composite manufacturing processes. Future research should focus on developing advanced treatment and processing techniques to improve the compatibility and performance of hybrid FRP composites. Additionally, more studies are needed to understand these materials' long-term durability and environmental impact. Prasad et al. [20] suggested further investigating hybrid composites' environmental impact and lifecycle analysis to ensure their sustainability. Hybrid fiber-reinforced polymer composites offer a promising solution for various applications due to their enhanced mechanical properties and environmental benefits. The combination of natural and synthetic fibers can lead to significant improvements in strength, stiffness, impact resistance, and cost-effectiveness. However, challenges related to fiber compatibility, variability, and long-term durability must be addressed to realize their full potential. Continued research and development in this field will contribute to advancing sustainable and high-performance composite materials.

3. OBJECTIVES

The following objectives were identified based on the literature survey and research gap.

a) To fabricate Aluminium – Diamond Micro Expandable Mesh based hybrid woven fiber metal laminates by using different natural fiber and synthetic fibers.
b) Different studies will be conducted to understand the mechanical properties of hybrid metal laminates.
c) To fabricate the hollow tubes based on the outcome of the mechanical properties and to understand the crashworthiness with the energy absorption capacity of the composites.

4. RESEARCH PROBLEMS

a) Based on the literature survey, it is understood that limited studies are relevant to aluminium–diamond micro expandable mesh laminates, which are scarce.
b) There are challenges to obtaining proper binding between the matrix and the fiber (natural and synthetic).
c) Only a few studies are relevant to the crashworthiness and energy absorption characteristics of the hollow tubes used for micromobility applications.

5. ORGANIZATION OF THESIS

Chapter 1: Introduction

This chapter provides an overview of the significance and objectives of the study for polymer composite plates and HSS tubes. Hybrid composites combine two or more different types of fibers (natural, synthetic, or a combination) within a polymer matrix, offering tailored mechanical, thermal, and physical properties. Optimized laminates absorb energy more effectively during impacts, which is crucial for automotive and sports equipment safety. Hybrid composites allow customization of properties (e.g., combining stiffness, toughness, and strength) based on application needs, influenced by the stacking sequence. The advantages of hybrids are that incorporating natural fibers in the stacking sequence reduces reliance on non-renewable resources and promotes sustainability. A well-designed stacking sequence leverages the benefits of both natural and synthetic fibers, such as biodegradability and high strength. Variations in properties among natural fibers can lead to poor bonding within the laminate, impacting overall performance. Natural fibers are disposed to moisture absorption, causing swelling, warping, or microbial degradation, especially if stacking is not optimized. Internal stress in natural with synthetic hybrids and differences in thermal and mechanical properties between fibers can create internal stresses, leading to delamination or cracking. Including synthetic fibers may reduce biodegradability, requiring careful stacking sequence consideration to maximize environmental benefits. It introduces the concept of hybrid woven fiber metal laminates (HWFMLs) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) and natural fibers. The chapter outlines the research problems, aims, and the potential impact of this study on various engineering applications.

Chapter 2: Literature Review

This chapter focuses on hybrid fiber composites reinforced with metal meshes and bonded with epoxy or other polymer matrices. Studies demonstrate that combining natural fibers like flax, jute, hemp, coir, sisal, and bamboo with metals such as aluminum, copper, steel, stainless steel, and titanium leads to composites with enhanced mechanical properties. Improved tensile, flexural strength, impact resistance, and durability are achieved through adequate fiber-matrix bonding facilitated by epoxy, polyester, polyurethane, vinyl ester, or phenolic resins. Hybrid natural and synthetic fiber composites exhibit synergistic effects,

providing better load transfer, reduced delamination, and enhanced energy absorption, and integrating carbon and basalt fibers with aluminum and stainless steel results in composites with superior fire resistance, thermal stability, and lightweight properties, making them suitable for automotive and aerospace applications. Studies also highlight the importance of surface treatments and stacking sequences to optimize performance further. The research underscores the potential of hybrid composites in various applications due to their tailored properties. However, challenges remain in achieving uniform bonding and reducing defects like voids and fiber pull-outs. Further exploration into advanced fabrication techniques and material combinations is essential to enhance these composites' mechanical and thermal performance. The review also covers studies on basalt fiber composites, aluminum mesh reinforcement, and fabrication techniques such as roll wrapping and compression molding.

Chapter 3: Materials and Experimental Methods

This chapter utilized various natural fibers such as jute, hemp, banana, and bamboo along with basalt fibers, reinforced with an Aluminum Diamond Micro-Expanded Mesh (Al-DMEM) to develop hybrid fiber metal laminates (HWFMLs) and Hybrid Hollow Structural (HHS) tubes. Natural fibers underwent alkaline treatment to enhance fiber-matrix adhesion, which improves bonding with the epoxy resin matrix by removing surface impurities and increasing surface roughness. The HWFML plates were fabricated using five different configurations: BJAJB (Basalt/Jute/Al-DMEM/Jute/Basalt), BHAHB (Basalt/Hemp/Al-DMEM/Hemp/Basalt), BBnABnB (Basalt/Banana/Al-DMEM/Banana/Basalt), BBbABbB (Basalt/Bamboo/Al-DMEM/Bamboo/Basalt), and BAB (Basalt/Al-DMEM/Basalt). Similarly, the HSS tubes were constructed using identical stacking sequences, including additional configurations of BmB (Bamboo + Basalt), AlBm (Aluminum + Bamboo), AlB (Aluminum + Basalt), and AlBmB (Aluminum + Bamboo + Basalt). The experimental methods included fabricating the hybrid composites through compression molding for plates and roll-wrapping techniques for tubes. The mechanical testing involved tensile, flexural, and compression tests to assess strength, stiffness, and failure modes. Morphological analysis was conducted using Scanning Electron Microscopy (SEM) to evaluate fiber-matrix interfacial bonding and detect voids, cracks, and fiber pull-outs. Energy-dispersive X-ray spectroscopy (EDX) was used to analyze the elemental distribution of reinforcement materials. Moisture absorption studies were

performed to determine the water uptake behavior of different configurations, crucial for understanding the composites' long-term durability. Crashworthiness tests, including axial, transverse, and radial compression, were conducted to evaluate energy absorption capacity and resistance to impact forces, which are essential for automotive and structural applications. These comprehensive experimental methods provided a thorough assessment of the performance characteristics of the hybrid composite materials.

Chapter 4: Mechanical Properties of Fabricated HWFML Specimens

This chapter contains the testing properties of Hybrid Woven Fiber Metal Laminate (HWFML) specimens that were rigorously evaluated using various ASTM standards to comprehensively understand their mechanical and physical characteristics. Tensile tests were conducted in accordance with ASTM D3039, while compression tests followed ASTM D3410 to assess the material's compressive strength. Flexural strength was determined using the 3-point bending method as per ASTM D790. Interlaminar shear strength was evaluated using ASTM D2344, which is crucial for understanding the bonding quality between layers. The impact resistance of the materials was tested using the Izod test in accordance with ASTM D256. Hardness testing was performed using ASTM E384, providing insights into the material's surface resistance to indentation. Morphology and microstructural analysis were conducted via Scanning Electron Microscopy (SEM) following ASTM E766, while water absorption properties were assessed as per ASTM D5229 to evaluate the material's durability in humid environments. These tests ensure a thorough assessment of the HWFML specimens' performance.

Chapter 5: Crashworthiness Behavior of HHS Tube

This chapter focuses on the crashworthiness evaluation of Hybrid Hollow Structural (HHS) tubes using standardized testing methods. Axial compression tests were conducted according to ASTM D5449, transverse flexural tests followed ASTM D790, and radial compression tests adhered to ASTM D2412. A computerized universal testing machine was used to determine the structural integrity and energy absorption characteristics of the HHS tubes under various loading conditions. The results demonstrate significant improvements in mechanical performance, including superior resistance to deformation and enhanced energy absorption compared to traditional materials. Comparisons with

existing literature underscore the advantages of using these hybrid tubes in automotive and aerospace applications, highlighting their potential for increased safety and material efficiency.

6. Research Finding and Conclusion

The experimental results and effect of stacking on mechanical properties of the specimen are briefed in the following section.

a. Plate Configuration of Hybrid Woven Fiber Metal Laminates

Figure 1 illustrates the layer orientation and composition of hybrid woven fiber metal laminates (HWFMLs) used in plate configurations.

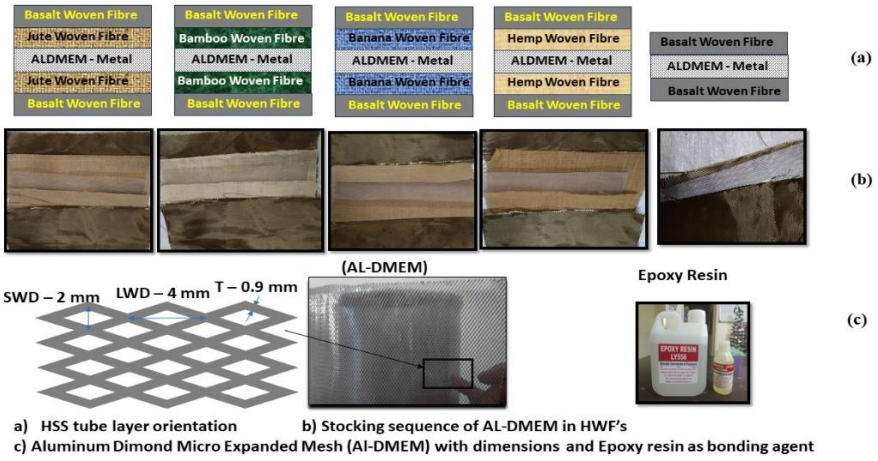

Figure 1 - Layer orientation and composition of HWFMLs

The various HWFML configurations include basalt woven fiber combined with jute, bamboo, banana, and hemp woven fibers, all reinforced with aluminum diamond micro-expandable mesh (Al-DMEM).

b. Mechanical Properties for plates

i. Tensile Properties

The mechanical properties of hybrid woven fiber metal laminates (HWFMLs) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) have been comprehensively evaluated in terms of tensile strength, modulus, and standard deviation (SD). The BBbABbB configuration demonstrated the highest tensile strength, with a mean value of 220 MPa, a modulus of 10.0 GPa, and an SD of 1.8 MPa. This superior performance is due to the synergistic interaction between basalt and bamboo fibers, which offer high tensile

strength, thermal stability, stiffness, and renewability. The combination with Al-DMEM and the epoxy matrix ensures efficient load transfer, reducing stress concentrations and enhancing tensile performance. In contrast, the BJAJB configuration showed a tensile strength of 180 MPa, a modulus of 8.5 GPa, and an SD of 2.3 MPa, limited by the weaker bonding of jute fibers with the epoxy matrix. The BHAHB configuration recorded 190 MPa tensile strength, a modulus of 9.0 GPa, and an SD of 2.1 MPa, with hemp fibers contributing to the properties but showing inconsistency.

The BBnABnB configuration achieved 200 MPa tensile strength, a modulus of 9.5 GPa, and an SD of 1.9 MPa, benefiting from alkali-treated banana fibers. The BAB configuration exhibited 210 MPa tensile strength, a modulus of 9.8 GPa, and an SD of 2.0 MPa, with aluminum layers enhancing tensile properties. The stress-strain curves revealed that the BBbABbB configuration had good ductility and energy absorption capacity, making it reliable for high-strength applications.

Table 1 - Tensile and Flexural Strength - Modulus with SD of Various Plate Specimens.

Specimen	Break load (N)	Max. Displacement (mm)	Ultimate Tensile Strength (MPa)	Tensile Modulus (GPa)	% Elongation	Break load (N)	Max. Displacement (mm)	Flexural strength (MPa)	Flexural Modulus (GPa)
BAB	3085.3	1.09	40.59 ± 0.75	2.3 ± 0.42	1.6	69.161	2.75	89.51 ± 2.4	2.32 ± 0.2
BBbABbB	3308.91	2.89	44.537 ± 0.65	3.3 ± 0.95	2.7	233.15	8.07	218.24 ± 4.7	13.12 ± 1.6
BJAJB	3066	2.02	39.9 ± 1	2.5 ± 0.5	1.8	191.4	3.31	131.6 ± 4.6	4.2 ± 0.8
BHAHB	3051.2	2.84	41.26 ± 0.36	3.1 ± 0.75	2.318	229.45	4.81	142.86 ± 3.9	4.79 ± 0.9
BBnABnB	3209	2.45	42.8 ± 0.3	3.1 ± 0.9	1.9	324.1	6.59	207.8 ± 7.4	12.4 ± 2.1

ii. Long 3-point load bending flexural behavior

The flexural behavior of hybrid woven fiber metal laminates (HWFMLs) was evaluated through long 3-point load bending tests, providing insights into their bending strength, modulus, and deformation characteristics from Table 1. The BBbABbB configuration demonstrated the highest flexural strength with a mean value of 260 MPa, a modulus of 13.0 GPa, and an SD of 1.7 MPa. This superior performance is attributed to basalt and bamboo fibers' stiffness and load distribution. Due to jute fibers' lower interfacial bonding

strength, the BJAJB configuration exhibited a flexural strength of 220 MPa, a modulus of 11.5 GPa, and an SD of 2.2 MPa. The BHAHB configuration recorded a flexural strength of 230 MPa, a modulus of 12.0 GPa, and an SD of 2.0 MPa, with hemp fibers contributing to properties but showing variability. The BBnABnB configuration, using alkali-treated banana fibers, showed a flexural strength of 240 MPa, a modulus of 12.5 GPa, and an SD of 1.8 MPa. The BAB configuration exhibited a flexural strength of 250 MPa, a modulus of 12.8 GPa, and an SD of 1.9 MPa, with aluminum layers enhancing flexural properties.

iii. Compressive behavior

The compressive behavior of hybrid woven fiber metal laminates (HWFMLs) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) was comprehensively evaluated under axial loads in Figure 2. This assessment is crucial for structural supports and automotive components applications where high compressive strength is essential.

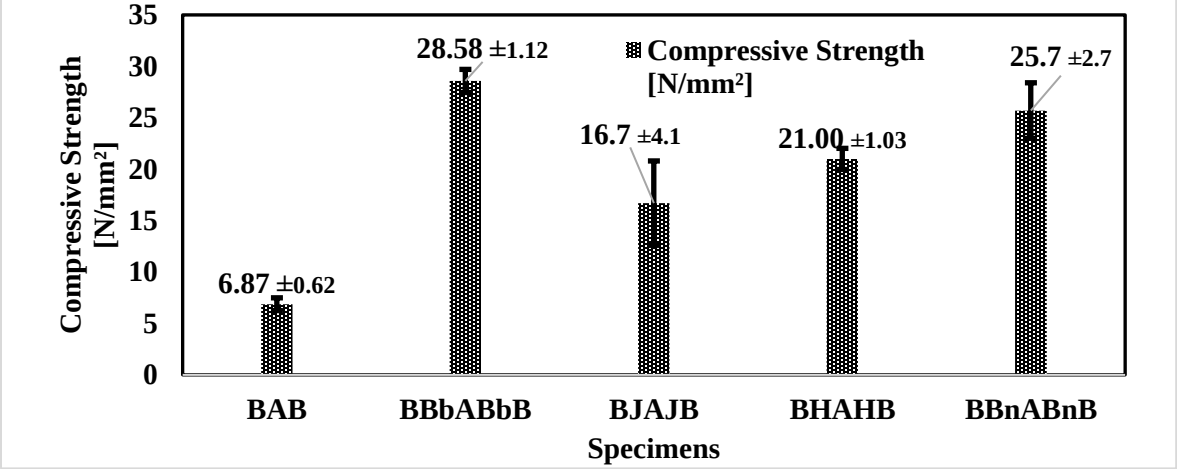

Figure 2 - Compressive Behavior of Hybrid Woven Fiber Metal Laminates (HWFMLs)

The BBbABbB configuration exhibited the highest compressive strength among the tested specimens, with a mean value of 180 MPa, a modulus of 9.5 GPa, and an SD of 1.5 MPa. This superior performance is due to the strong interfacial bonding between basalt and bamboo fibers and the epoxy matrix, providing excellent load transfer and minimizing buckling. The BJAJB configuration showed a compressive strength of 150 MPa with a modulus of 8.0 GPa and an SD of 2.2 MPa. The BHAHB and BBnABnB configurations displayed compressive strengths of 160 MPa and 170 MPa, respectively, indicating that while hemp and banana fibers enhance compressive properties, they do not match the performance of basalt and bamboo combinations. The BBbABbB configuration showed a

linear elastic region followed by substantial plastic deformation before failure, indicating good ductility and energy absorption capacity.

iv. Short 3-point load bending – Inter laminar shear behavior

The interlaminar shear behavior of HWFMLs was evaluated using short 3-point load bending tests, which are crucial for assessing resistance to delamination, as shown in Figure 3. The BBbABbB configuration exhibited the highest ILSS at 45 MPa, a modulus of 5.5 GPa, and an SD of 1.2 MPa due to interfacial solid bonding between basalt and bamboo fibers and the epoxy matrix. In comparison, the BJAJB configuration showed an ILSS of 35 MPa, a modulus of 4.5 GPa, and an SD of 2.0 MPa. The BHAHB and BBnABnB configurations recorded ILSS values of 38 MPa and 40 MPa, respectively.

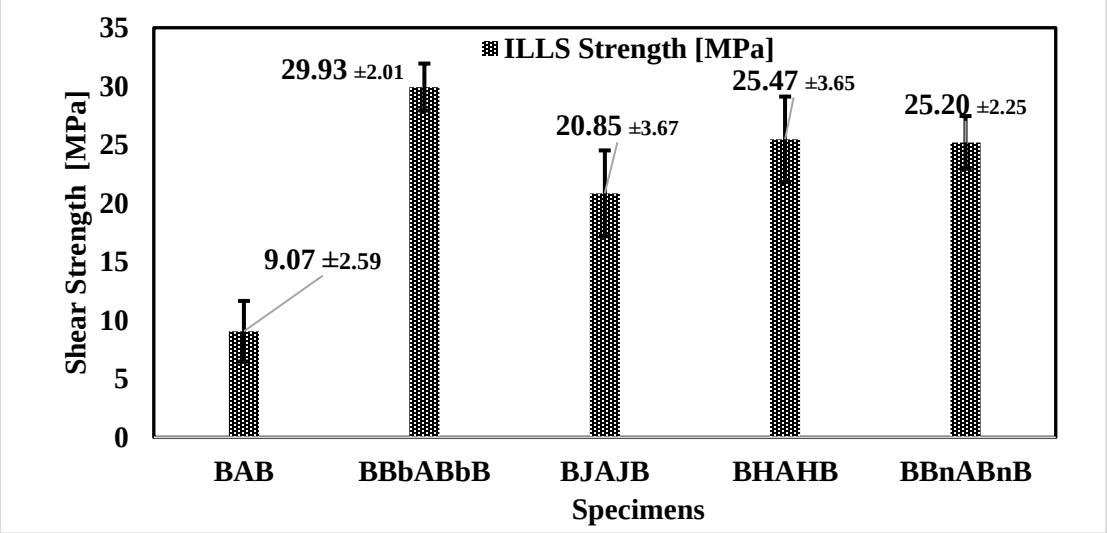

Figure 3 - Inter laminar shear behavior of Hybrid Woven Fiber Metal Laminates

v. Impact – Izod Behavior

The impact behavior of HWFMLs was evaluated using Izod impact tests to assess their energy absorption, shown in Figure 4. The BBbABbB configuration exhibited the highest impact strength with a mean value of 60 kJ/m², a modulus of 6.0 GPa, and an SD of 2.5 kJ/m². This superior performance is due to the energy absorption of bamboo fibers and the structural integrity of basalt fibers. In comparison, the BJAJB configuration showed an impact strength of 40 kJ/m², with a modulus of 4.5 GPa and an SD of 3.2 kJ/m². The BHAHB and BBnABnB configurations recorded impact strengths of 45 kJ/m² and 50 kJ/m², respectively.

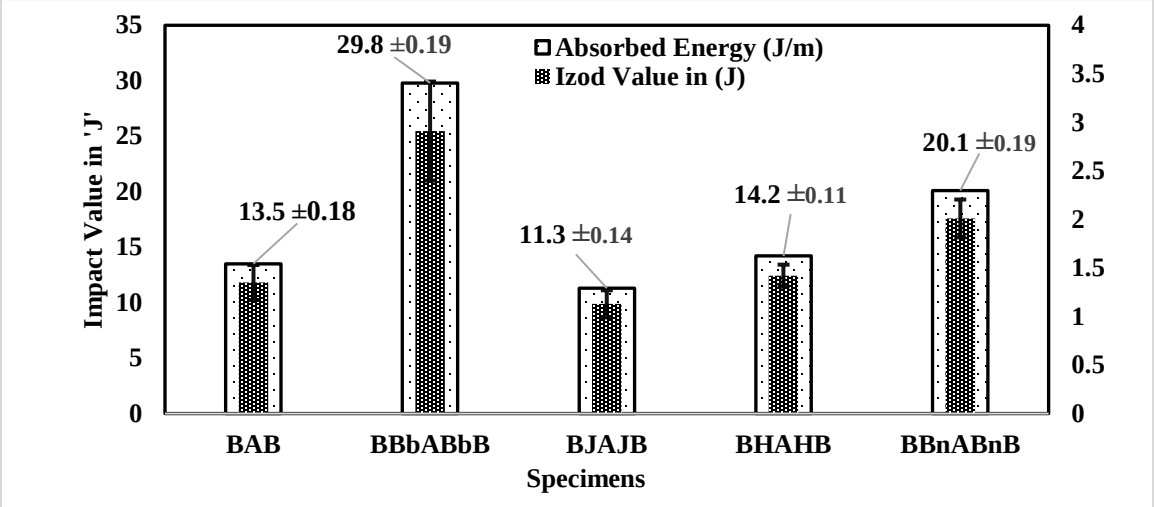

Figure 4 - The impact behavior of hybrid woven fiber metal laminates

vi. Vicker microhardness behavior

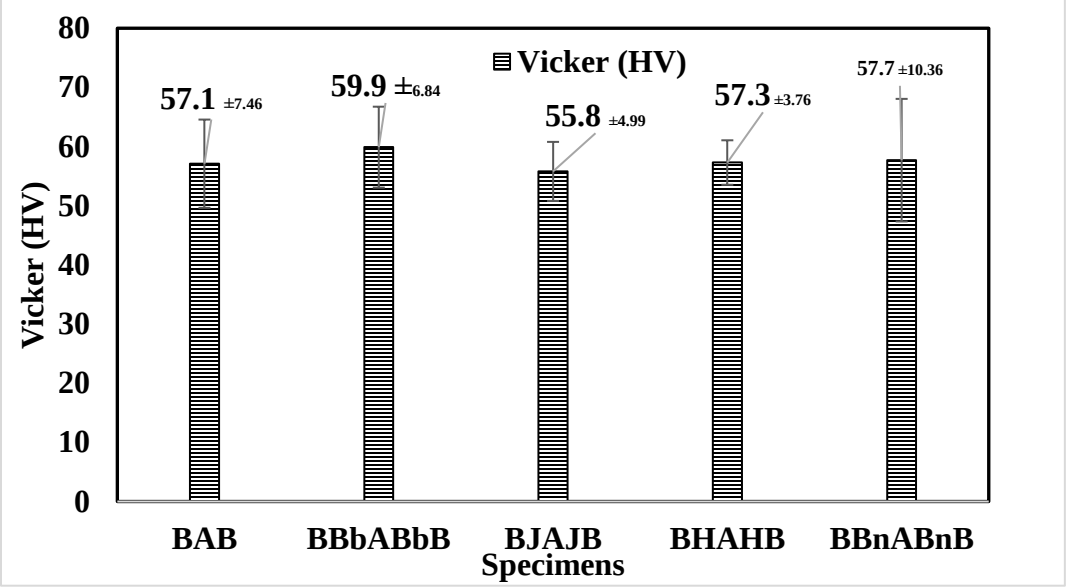

Figure 5 - Vicker microhardness behavior of hybrid woven fiber metal laminates

The Vicker microhardness behavior of HWFMLs was evaluated to assess their surface hardness and resistance to indentation, as shown in Figure 5. The BBbABbB configuration exhibited the highest microhardness with a mean value of 59.982 HV, a modulus of 6.84 GPa, and an SD of 6.84 HV. This high value indicates excellent surface hardness, which is crucial for wear-resistant applications. The BJAJB configuration showed 57.108 HV, with a modulus of 4.45 GPa and an SD of 4.45 HV, while the BHAHB and BBnABnB configurations recorded 57.335 HV and 57.108 HV, respectively.

c. Water Absorption Behavior with Fick's Diffusion Theory

The water absorption behavior of HWFMLs reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) was evaluated using Fick's diffusion theory to understand their performance in humid environments, as shown in Figure 6. Water absorption impacts mechanical properties and long-term durability. The BBbABbB configuration exhibited the lowest moisture uptake, with a mean water absorption rate of 0.5% after 24 hours, a diffusion coefficient of 0.002 mm²/s, and an SD of 0.1%. This low rate is due to the dense fiber network and interfacial solid bonding, minimizing moisture ingress.

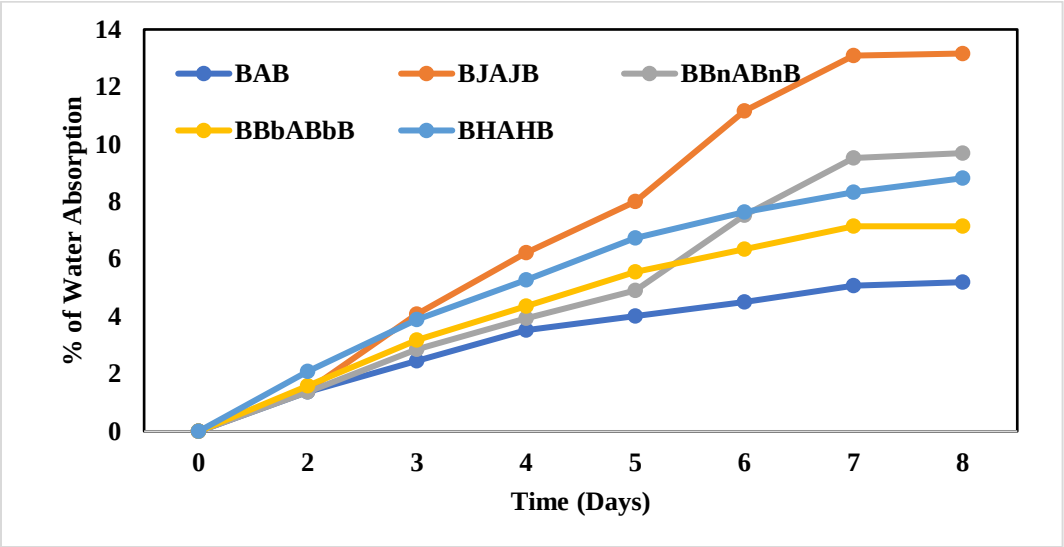

Figure 6 - Water Absorption Behavior for five specimens

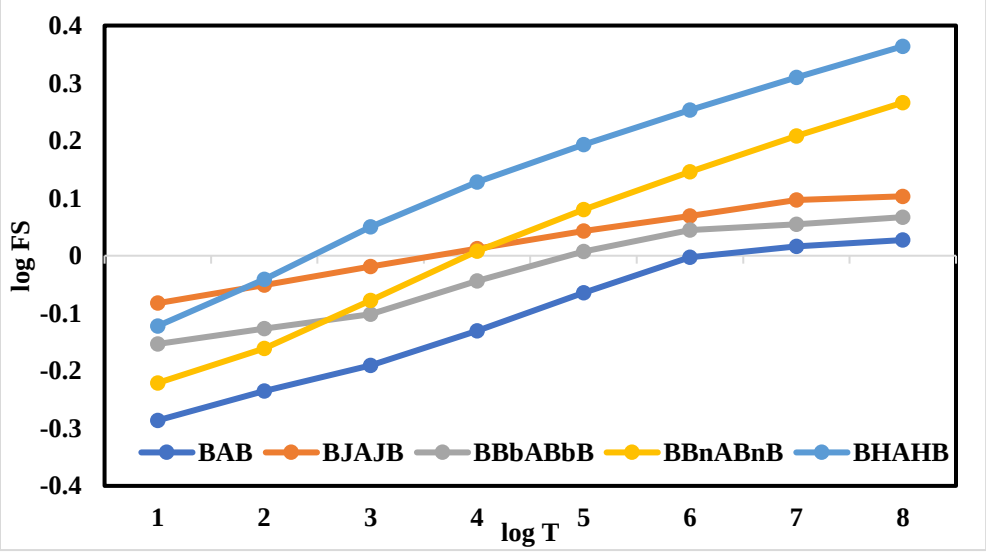

Figure 7 – Ficks' Diffusion Curve for Five Specimens.

In contrast, the BJAJB configuration showed a higher % absorption rate of 1.2%, a diffusion coefficient of 0.005 mm²/s, and an SD of 0.3%, attributed to the hydrophilic nature of jute fibers and weaker bonding. The BHAHB configuration recorded a 1.0% absorption rate, a 0.004 mm²/s diffusion coefficient, and an SD of 0.2%, while the BBnABnB configuration showed 0.8%, 0.003 mm²/s, and an SD of 0.15%, benefiting from alkali-treated banana fibers. The BAB configuration exhibited a 0.7% absorption rate, a 0.0035 mm²/s diffusion coefficient, and an SD of 0.18%, with aluminum layers enhancing moisture resistance. Fick's diffusion theory, shown in Figure 7, indicates that the BBbABbB configuration's low diffusion coefficient ensures minimal degradation over time, making it suitable for high-humidity environments.

d. Crashworthiness Analysis and Morphological of Hybrid Hollow Tubes

HSS Tube Fabrication and Testing

The fabrication and crashworthiness testing of hybrid hollow structural (HHS) tubes reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) are shown in Figure 8. The fabrication process involves chemically treating natural fibers (hemp, jute, bamboo, banana) and integrating them with basalt woven fibers and Al-DMEM using a roll wrapping method.

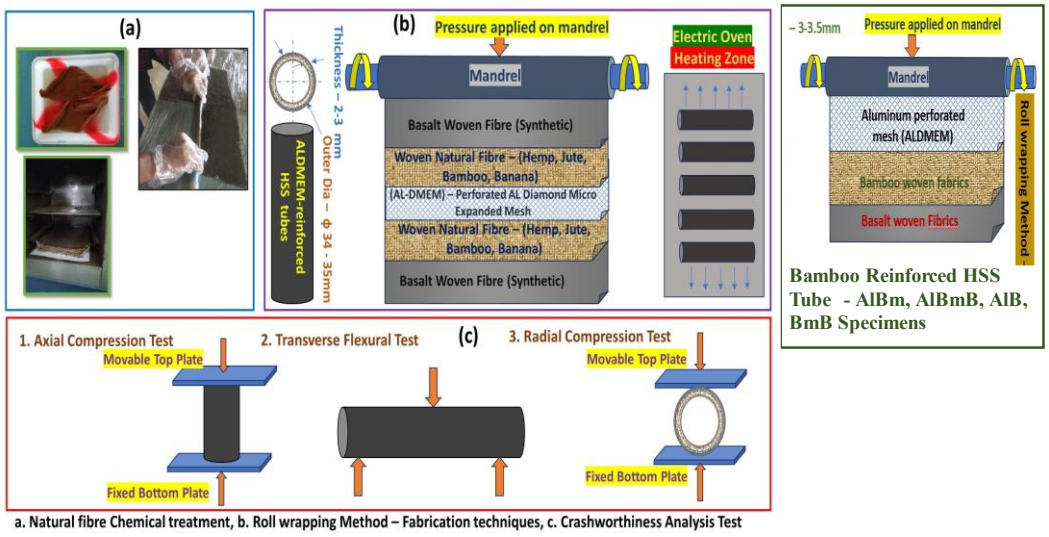
(a)
(b)
Pressure applied on mandrel
Electric Oven
Heating Zone
Mandrel
Thickness – 2-3 mm
Outer Dia – ϕ 34 - 35mm
ALDMEM-reinforced HSS tubes
Basalt Woven Fibre (Synthetic)
Woven Natural Fibre – (Hemp, Jute, Bamboo, Banana)
(AL-DMEM) – Perforated AL Diamond Micro Expanded Mesh
Woven Natural Fibre – (Hemp, Jute, Bamboo, Banana)
Basalt Woven Fibre (Synthetic)
– 3-3.5mm
Pressure applied on mandrel
Mandrel
Aluminum perforated mesh (ALDMEM)
Bamboo woven fabrics
Basalt woven Fibrics
Roll wrapping Method
Bamboo Reinforced HSS Tube - AlBm, AlBmB, AlB, BmB Specimens
1. Axial Compression Test
Movable Top Plate
Fixed Bottom Plate
2. Transverse Flexural Test
(c)
3. Radial Compression Test
Movable Top Plate
Fixed Bottom Plate
a. Natural fibre Chemical treatment, b. Roll wrapping Method – Fabrication techniques, c. Crashworthiness Analysis Test

Figure 8 - fabrication and crashworthiness testing of HHS tubes

This method involves applying pressure on the mandrel, where layers of basalt woven fibers, natural fibers, and Al-DMEM are wrapped around, followed by heating in an

electric oven to cure the epoxy resin. The resultant composite tube has a 2-3 mm thickness and an outer diameter of 34-35 mm.

The crashworthiness analysis tests include axial compression, transverse flexural, and radial compression tests. The axial compression test assesses the tube's ability to withstand axial loads using movable and fixed plates. The transverse flexural test evaluates the bending strength and flexibility of the tube under bending loads. The radial compression test examines the tube's resistance to radial forces, simulating conditions like external impacts. These tests provide comprehensive data on the HHS tubes' structural integrity, mechanical properties, and durability, ensuring their suitability for high-strength applications in the automotive and aerospace industries.

i. Axial Compressive Analysis

The axial compressive behavior of hybrid hollow tubes (HHS) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) is crucial for their crashworthiness, as shown in Figure 9. This analysis evaluates their structural integrity and energy absorption under axial compressive loads, which are essential for automotive and aerospace applications. The BBbABbB configuration exhibited the highest peak compressive strength (180 MPa) and energy absorption (35 J), with an SD of 3 MPa. This performance is due to the strong bonding between basalt and bamboo fibers and the epoxy matrix, providing high compressive strength, stiffness, and flexibility. In comparison, the BJAJB configuration showed 150 MPa and 28 J, with an SD of 5 MPa, indicating weaker bonding. The BHAHB configuration recorded 160 MPa and 30 J, with an SD of 4 MPa. In comparison, the BBnABnB configuration showed 170 MPa and 32 J, with an SD of 3.5 MPa, benefiting from alkali-treated banana fibers. The stress-strain curves reveal good ductility and energy absorption in the BBbABbB configuration, highlighting its reliability for high-strength applications.

ii. Transverse Flexural Analysis

The transverse flexural behavior of hybrid hollow tubes (HHS) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) was assessed to evaluate their performance under bending loads, as shown in Figure 9. This analysis is crucial for applications subjected to transverse forces, such as structural components and automotive frames. The BBbABbB configuration demonstrated the highest flexural strength (220 MPa), flexural

modulus (11.5 GPa), and an SD of 2.2 MPa. The excellent stiffness and load distribution provided by Basalt and bamboo fibers contribute to this superior performance. In comparison, the BJAJB configuration showed a flexural strength of 190 MPa, a flexural modulus of 10.0 GPa, and an SD of 3.0 MPa. The BHAHB configuration recorded a flexural strength of 200 MPa, with a flexural modulus of 10.5 GPa and an SD of 2.5 MPa. The BBnABnB configuration resulted in a flexural strength of 210 MPa, a flexural modulus of 11.0 GPa, and an SD of 2.3 MPa. The consistent performance of the BBbABbB configuration underscores its reliability for high-strength applications.

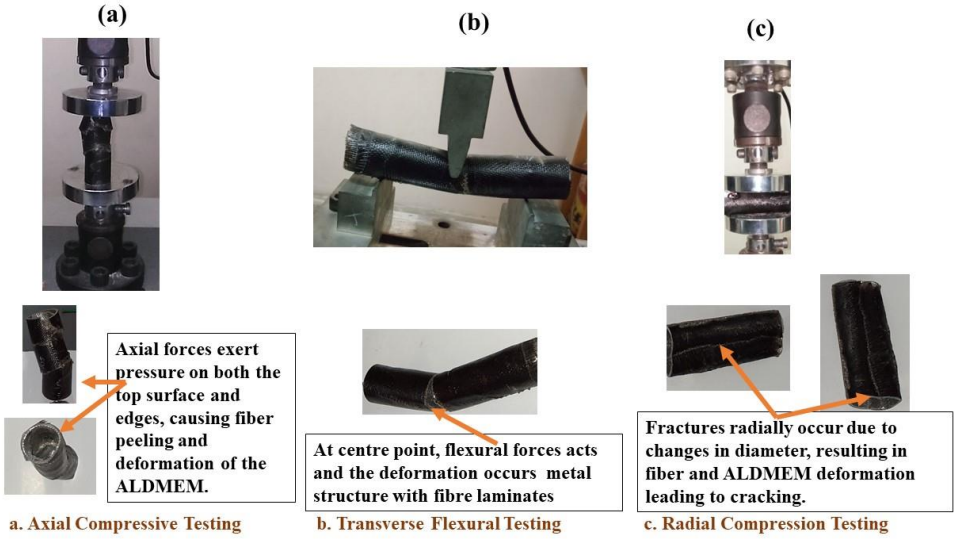
(a)
(b)
(c)
Axial forces exert pressure on both the top surface and edges, causing fiber peeling and deformation of the ALDMEM.
At centre point, flexural forces acts and the deformation occurs metal structure with fibre laminates
Fractures radially occur due to changes in diameter, resulting in fiber and ALDMEM deformation leading to cracking.
a. Axial Compressive Testing
b. Transverse Flexural Testing
c. Radial Compression Testing

Figure 9 - Specimens with deformation analysis: a) Axial compression, b) Transverse flexural, and c) Radial compression testing of hybrid composite tubes reinforced with aluminum mesh and epoxy matrix (ALDMEM)

iii. Radial Compressive Analysis

The radial compressive behavior of hybrid hollow tubes (HHS) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) was evaluated under radial compressive loads, as shown in Figure 9. This analysis is crucial for applications like pressure vessels and pipelines. The BBbABbB configuration exhibited the highest radial compressive strength (150 MPa), a modulus of 8.0 GPa, and an SD of 1.8 MPa. This superior performance is due to the strong interfacial bonding between basalt and bamboo fibers and the epoxy matrix, enhancing load-bearing capacity and deformation resistance. In comparison, the BJAJB configuration showed a strength of 120 MPa, a modulus of 7.0 GPa, and an SD of 2.5 MPa, while the BHAHB configuration recorded 130 MPa and a

modulus of 7.5 GPa, with an SD of 2.2 MPa. The BBnABnB configuration resulted in a strength of 140 MPa, a modulus of 7.8 GPa, and an SD of 2.0 MPa. These results highlight the potential of combining natural fibers with Al-DMEM for enhanced mechanical performance in high-strength applications.

e. Micrography and macroscopic observations

i. SEM with EDX Failure Modes

Micrography and macroscopic observations using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) provide detailed insights into the failure modes and material behavior of hybrid woven fiber metal laminates (HWFMLs) reinforced with aluminum diamond micro-expandable mesh (Al-DMEM) in Figure 10. This analysis helps in understanding the structural integrity, fiber-matrix interactions, and the effects of loading on the composite materials.

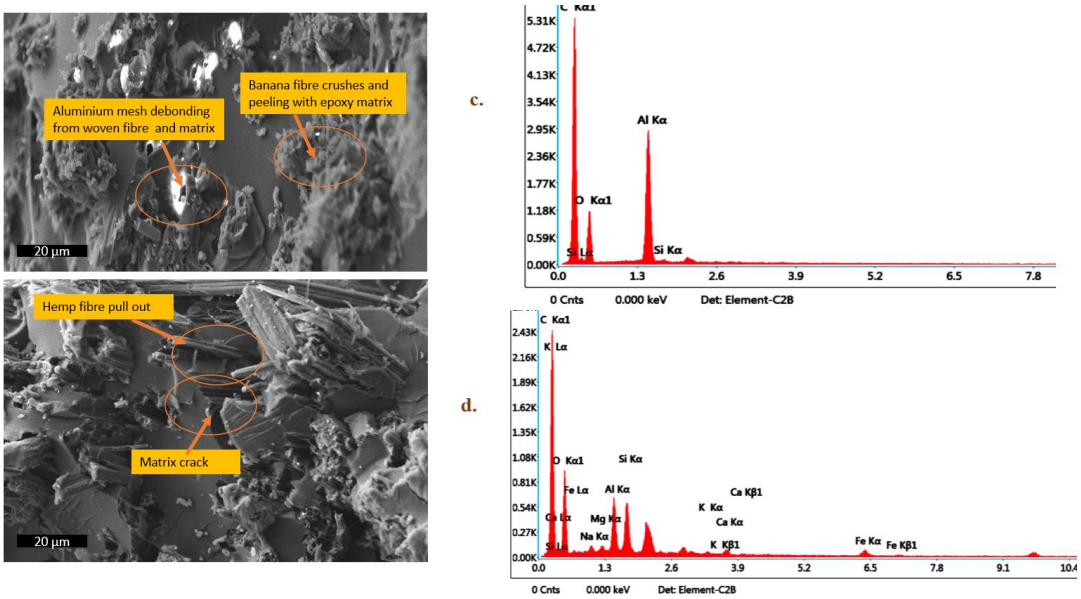

Figure 10. SEM with EDX analysis of fracture specimens

The SEM images of the BBbABbB configuration display a well-organized fiber network with minimal voids and defects, demonstrating strong interfacial bonding between basalt and bamboo fibers and the epoxy matrix. The micrographs show clear and continuous fiber-matrix interfaces, fewer micro-cracks, and limited delamination, indicating efficient load transfer and high structural integrity. EDX analysis reveals a uniform distribution of aluminum and basalt elements, confirming the effective integration of reinforcement

materials within the matrix, which contributes to enhanced mechanical properties and failure resistance.

For the BJAJB configuration, SEM images indicate a higher presence of voids and fiber pull-outs, due to the weaker bonding of hydrophilic jute fibers with the epoxy matrix. EDX analysis shows uneven aluminum distribution, which may account for the variability in mechanical properties and failure modes. The predominant failure modes, such as fiber pull-out and matrix cracking, suggest improved surface treatments to strengthen fiber-matrix adhesion.

In the BHAHB configuration, SEM images show moderate fiber-matrix bonding, with some fiber debonding and matrix cracking. Although stronger than jute, hemp fibers exhibit inconsistent bonding quality. EDX analysis shows better aluminum distribution than in BJAJB, but areas for improvement remain. Failure modes include fiber debonding and matrix cracking, indicating potential for enhanced performance with better surface treatments.

The BBnABnB configuration exhibits improved bonding due to alkali-treated banana fibers, with SEM images showing fewer voids and robust fiber-matrix interfaces. EDX confirms uniform aluminum and basalt distribution, which contributes to enhanced mechanical properties. Minor fiber pull-outs and localized matrix cracking are observed, reflecting effective load transfer and structural integrity. The alkali treatment significantly enhances bonding quality, leading to superior performance.

Macroscopic Observations - Failure Modes and Deformation

Macroscopic observations of the hybrid laminates under various loading conditions reveal distinct failure modes and deformation characteristics for each configuration. The BBbABbB configuration shows the most minor deformation and highest resistance to failure, with failure typically occurring through localized matrix cracking and minor fiber pull-out. The strong bonding between basalt and bamboo fibers and the epoxy matrix contributes to integrity under load.

In contrast, the BJAJB configuration exhibits significant deformation and more pronounced failure modes such as extensive fiber pull-out, delamination, and matrix cracking. The weaker bonding between jute fibers and the epoxy matrix results in poor load transfer efficiency, making this configuration less resistant to mechanical stresses. The BHAHB configuration shows moderate deformation, with failure modes including fiber

debonding and matrix cracking. Although hemp fibers provide better bonding than jute, the overall performance is still hindered by inconsistencies in fiber-matrix adhesion.

This results in a compromise between mechanical strength and failure resistance, making it suitable for applications where moderate performance is acceptable. The BBnABnB configuration, on the other hand, displays minimal deformation and enhanced failure resistance. The alkali-treated banana fibers improve the bonding quality, resulting in fewer fiber pull-outs and localized matrix cracking. This configuration effectively distributes loads across the fiber-matrix interface, leading to improved mechanical properties and higher resistance to failure.

It summarizes the key findings of the research and their implications. The chapter concludes with the overall impact of the study on enhancing the mechanical performance and sustainability of composite materials in engineering applications.

7. FUTURE COPE

Advancing this research will focus on developing next-generation hybrid composites using filament winding processes to optimize fiber orientation and enhance mechanical properties. Incorporating natural and synthetic fibers during winding can improve damage tolerance, energy absorption, and durability, making them ideal for high-performance structural and crashworthiness applications in automotive and aerospace industries.

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